

REVIEW

Potassium influences on yield and quality production for maize, wheat, soybean and cotton

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Potassium is one of the principle plant nutrients underpinning crop yield production and quality determination. While involved in many physiological processes, potassium's impact on water relations, photosynthesis, assimilate transport and enzyme activation can have direct consequences on crop productivity. Potassium deficiency can lead to a reduction in both the number of leaves produced and the size of individual leaves. Coupling this reduced amount of photosynthetic source material with a reduction in the photosynthetic rate per unit leaf area, and the result is an overall reduction in the amount of photosynthetic assimilates available for growth. The production of less photosynthetic assimilates and reduced assimilate transport out of the leaves to the developing fruit greatly contributes to the negative consequences that deficiencies of potassium have on yield and quality production. Goals aimed toward increasing crop productivity and improved quality dictate either increased potassium supply or more efficient use of potassium. Developing plants that more efficiently use potassium might be a worthwhile goal for geneticists.

Potassium (K^+) is one of major nutrients considered essential for crop growth and yield development, although it is not a integral component of any cellular organelle or structural part of the plant. It is the most abundant cation in plants and is associated or involved with many of the physiological processes supporting plant growth and development. Water relations, photosynthesis, assimilate transport and enzyme activation all can be impacted by potassium. Much of the earlier physiological work was conducted on plant parts, plant organelles or isolated membranes, with only a small portion carried out on whole intact plants or crop ecosystems. This article will briefly discuss the role potassium plays in a limited number of these physiological process (photosynthesis, assimilate transport, water relations and protein metabolism) and then trace how this physiological role translates into plant growth and development, yield production and crop quality determination for four major agronomic row crops: maize, wheat, soybean and cotton.

Physiological attributes

Considerable prior research has addressed the mechanisms of how potassium is absorbed by plant roots. Much of this research has been summarized in reviews by Leonard (1985) and Maathuis (1998) and in an review article for this series (Kronzucker and Britto 2008). Although outside the major thrust of this report, basically, potassium uptake in plants is biphasic, involving two processes, low-affinity K^+ uptake and high-affinity K^+ uptake. The low-affinity K^+ uptake can be thought of as a passive influx of K^+ down an electrochemical gradient using specific inward rectifying K channels. The high-affinity K^+ uptake involves an energy-dependent (ATP) inward K^+ pump against an electrochemical gradient usually in combination with an outflow of either H^+ or Na^+ .

The total amount of potassium absorbed by the crop during the growing season depends upon the crop species being grown, the amount of native soil K^+ , the amount of fertilizer K^+ applied, K^+ availability in the soil, the

environmental conditions during the growing season and the management practices employed (Eakin 1972, Mengel and Kirkby 1987, Mullins and Burmester 1998). The amount of K^+ actually removed from the field by a crop species depends upon the plant part or parts removed during harvest. For example, more K^+ is removed from a field where forage crops or sugar cane was grown because the majority of aboveground biomass is removed during harvest. In contrast, for grain and fiber crops in which only the seed and/or fiber is harvested, much less K^+ is actually removed from the field (Mullins and Burmester 1998). With maize (*Zea mays* L.) the majority of K^+ accumulation occurs before silking (Hanway 1962, Karlen et al. 1988). Similarly, most K^+ uptake in wheat (*Triticum* spp.) takes place as the shoot is undergoing its rapid phase of growth (Gregory et al. 1979). On the other hand, soybean [*Glycine max* (L.) Merr.] does not accumulate the majority of its K^+ until after flowering (Batchelor and Scott 1979, Karlen et al. 1982). Cotton (*Gossypium hirsutum* L.) also takes up the majority of its K^+ during the blooming and boll-filling period (Bassett et al. 1970, Mullins and Burmester 1990).

Once inside the plant, K^+ is involved with many physiological processes. Pioneering work by Fischer (1968) and Fischer and Hsiao (1968) demonstrated how the reversible K^+ flux into and out of stomatal guard cells controlled stomatal aperture by affecting osmotic potential of the guard cells. Further research revealed both K^+ and sucrose serve as the major osmoticums elevating the osmotic potential in open guard cells, with malate and Cl^- serving as the major counterions (Talbot et al. 1998). Guard cell K^+ uptake is mediated by K^+ -specific uptake channels and is coupled with proton extrusion into the apoplast (Hoth et al. 1997). Stomatal opening during the course of the day is thought to be a two-phase process with K^+ promoting opening early in the day and then giving way to sucrose as the principle driving osmotic force around midday (Talbot and Zeiger 1996). Because of this close coordination between K^+ guard cell concentration and stomatal aperture, insufficient leaf levels of K^+ can lead to decreased stomatal conductance (Bednarz et al. 1998, Huber 1985, Longstreth and Nobel 1980). As expected with this decrease in stomatal conductance, insufficient leaf K^+ levels also leads to decreased photosynthesis per unit leaf area (Bednarz et al. 1998, Huber 1985, Longstreth and Nobel 1980, Pier and Berkowitz 1987, Wolf et al. 1976). However, this decreased stomatal conductance only partially accounts for the photosynthetic decline observed with lower K^+ levels. Non-stomatal factors also contribute to this reduction in photosynthesis, particularly when the deficiency becomes extreme (Basile et al. 2003, Bednarz et al. 1998, Huber 1985, Tester and Blatt 1989). Bednarz

et al. (1998) reported that at the onset of a developing potassium deficiency, stomatal conductance was the principle factor limiting photosynthesis, whereas when the K^+ deficiency became more extreme, non-stomatal or biochemical factors became the overriding reason for the decreased photosynthesis. This biochemical limitation under low K^+ conditions is partly related to a chloroplast inner membrane ATPase that maintains the high stromal pH needed for efficient energy conversion from light to chemical energy by pumping protons out of the stroma into the cytosol while allowing K^+ flux into the stroma (Berkowitz and Peters 1993). Shingles and McCarty (1994) further demonstrated the importance of an adequate K^+ supply for optimal activity of that ATPase.

In addition to the reduced stomatal conductance and photosynthesis observed under K^+ deficient conditions, the transport of photosynthetic assimilates away from source tissue via the phloem is also restricted (Ashley and Goodson 1972, Mengel and Haeder 1977, Mengel and Viro 1974). This restriction on the transport of photosynthates can lead to an accumulation of sugars in the leaf tissue of K^+ -deficient plants (Bednarz and Oosterhuis 1999, Huber 1985, Pettigrew 1999) (Fig. 1). It is generally the hexose sugars, such as glucose and fructose, which accumulate rather than sucrose (Huber 1985). This accumulation of sugars undoubtedly contributes a small portion to the increased specific leaf weights observed when cotton plants were grown under conditions of low soil potassium (Pettigrew 1999, Pettigrew and Meredith 1997) (Table 1).

The osmotic role that K^+ serves in supporting stomatal opening also comes into play with supporting plant water relations and cell expansion. Potassium is the predominant inorganic osmoticum in the phloem and thus is

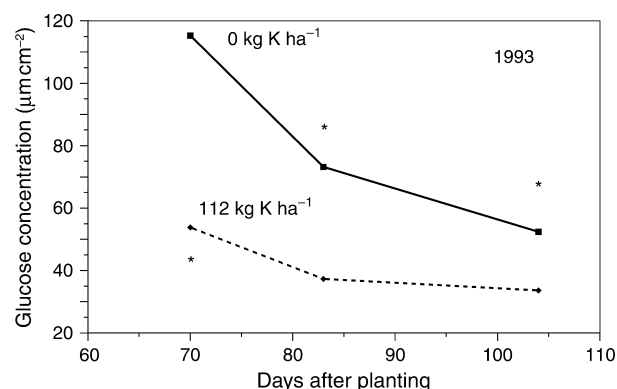


Fig. 1. Leaf glucose concentrations averaged across four cotton genotypes as affected by two K fertility levels (0 and 112 kg K ha⁻¹) at different days after planting in 1993 at Stoneville, MS. Asterisk denotes that differences between K fertility treatments are statistically significant at the 0.05 level (Pettigrew 1999).

Table 1. Cotton dry matter partitioning parameters as affected by two K fertilization rates at cutout averaged across two genotypes, two N fertilization rates and the years 1991 and 1992 (Pettigrew and Meredith 1997). ^aHarvest index = (total reproductive dry weight/total aboveground plant dry weight); ^bns, not significantly different at $P \geq 0.05$.

K application rate	Leaf area index	Specific leaf weight (g m^{-2})	Total dry weight (g m^{-2})	Main stem nodes (plant^{-1})	Harvest index ^a	Height (cm)
0 kg K ha^{-1}	2.61	53.0	587.3	19.5	0.32	124
112 kg K ha^{-1}	2.97	46.4	595.6	20.1	0.29	127
LSD 0.05	0.30	3.3	ns ^b	0.4	0.02	2

integral in the maintenance of turgor pressure for growing tissues, which are predominately supplied by the phloem (Mengel 1998). Mengel and Arneke (1982) demonstrated the importance of K^+ levels for maintaining proper water potential and turgor pressure and promoting cell elongation in the leaves of *Phaseolus vulgaris* L. plants. Individual cotton fibers are often used as model systems to study cell elongation because they are generally single cell structures that have elongated from normal epidermal cells to reach lengths of approximately 2.8 cm when mature. Using this system, Dhindsa et al. (1975) showed the importance of K^+ and malate as osmotica to produce the turgor pressure to drive cell expansion of individual cotton fibers (Fig. 2). When K^+ levels were insufficient or low, fiber elongation was reduced. Both malate and Cl^- often serve as the major counterions to balance K^+ in developing the osmotic potential and turgor pressure (Talbot et al. 1998).

Potassium is also involved directly or indirectly in plant protein metabolism (Blevins 1985). This involvement can begin with the stimulation of NO_3^- uptake and transport within the plant, as K^+ serves as the accompanying counter cation (Blevins et al. 1978a, 1978b). Furthermore, Mengel (1980) also demonstrated that the trans-

port of amino acids is enhanced by higher K^+ levels, especially the transport of amino acids to developing seeds. Potassium involvement is crucial for most in steps of the protein synthesis process, beginning with enzyme activation and continuing through ribosome synthesis and mRNA turnover (Blevins 1985, Evans and Wildes 1971). Although most of the Evans and Wildes (1971) research was performed using *Escherichia coli*, it is reasonable to assume that the findings would also be applicable to plants. Reinforcing the connection between K^+ levels and protein is the observation that crops with high seed protein concentrations also tend to have high K^+ harvest indices (amount of K^+ harvest in grain/total K^+ in grain and stover) (Blevins 1985).

Integrating the effect K^+ has on all of these physiological processes means that the K^+ level can have profound effects on crop growth and development. One of the more visually obvious consequences on plant growth from insufficient levels of plant potassium is a reduction in plant stature (Cassman et al. 1989, Ebelhar and Varsa 2000, Heckman and Kamprath 1992, Mullins et al. 1994, Pettigrew and Meredith 1997) (Table 1). This reduction in biomass because of a K^+ deficiency is often accompanied by a reduction in leaf

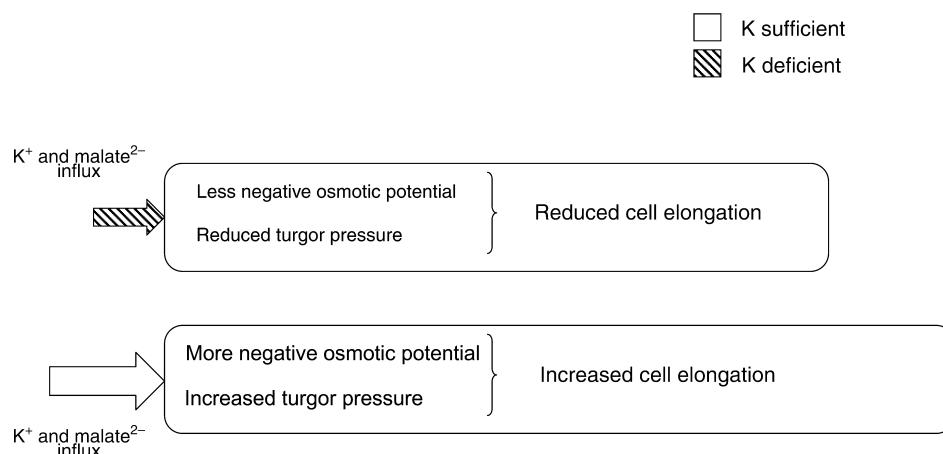


Fig. 2. Schematic diagram demonstrating the effect K has on osmotic potential and turgor pressure and ultimately cell elongation for contrasting K-sufficient and K-deficient plants.

area (Jordan-Meille and Pellerin 2004, Kimbrough et al. 1971, Pettigrew and Meredith 1997). In cotton, this leaf area reduction was also linked to a reduction in canopy sunlight interception (Gwathmey and Howard 1998, Pettigrew 2003) (Fig. 3). The leaf area reduction can come about through a reduction in the number of leaves produced, a reduction in the size of individual leaves or both. Insufficient K^+ levels reduced leaf area expansion leading to reduced leaf size in soybean (Huber 1985) and maize (Jordan-Meille and Pellerin 2004). The previously mentioned increase in specific leaf weight seen with K^+ (Pettigrew 1999, Pettigrew and Meredith 1997) is probably related to this reduction in leaf area expansion. Less leaf area may lead to an increased concentration of cellular components, carbohydrates and/or nutrients over a given unit of leaf area compared with leaves with adequate K^+ levels.

This combination of less leaf area, less solar radiation interception and reduced photosynthesis per unit leaf area under insufficient K^+ levels leads to a reduction in the total photosynthetic assimilate pool produced in the plants' source tissue (leaves). Coupling this reduced photoassimilate production with the restricted assimilate transport from the leaves results in a smaller total assimilate supply available for the sink tissue (reproductive tissue and other growing points) for K^+ -deficient plants. This reduced assimilate supply under a K^+ deficiency will ultimately diminish the yield and quality produced by those plants (Fig. 4).

Yield production

From the previous discussion, it should be clear that a properly managed K^+ fertility program is essential to achieve the maximum crop productivity. When soil and plant K^+ levels are not maintained at sufficient levels, economic losses can occur because of reduced production of grain, fiber or biomass. Much of this yield loss can be attributed to the aforementioned reduced overall production of photosynthetic assimilates when potassium levels are insufficient.

To achieve or maintain maximal maize yields, supplemental K^+ fertilization is often required, particularly on soils testing low for native available soil K^+ . Many researchers have reported maize yield increases in response to K^+ fertilization (Ebelhar and Varsa 2000, Heckman and Kamprath 1992, Mallarino et al. 1999). However, Bruns and Ebelhar (2006) did not find K^+ fertilization to improve grain yield, although they reported increased K^+ tissue concentrations as a result of K^+ fertilization. Part of the maize yield enhancement from K^+ fertilization is because of a reduction in stalk lodging with the K^+ fertilization, particularly when higher

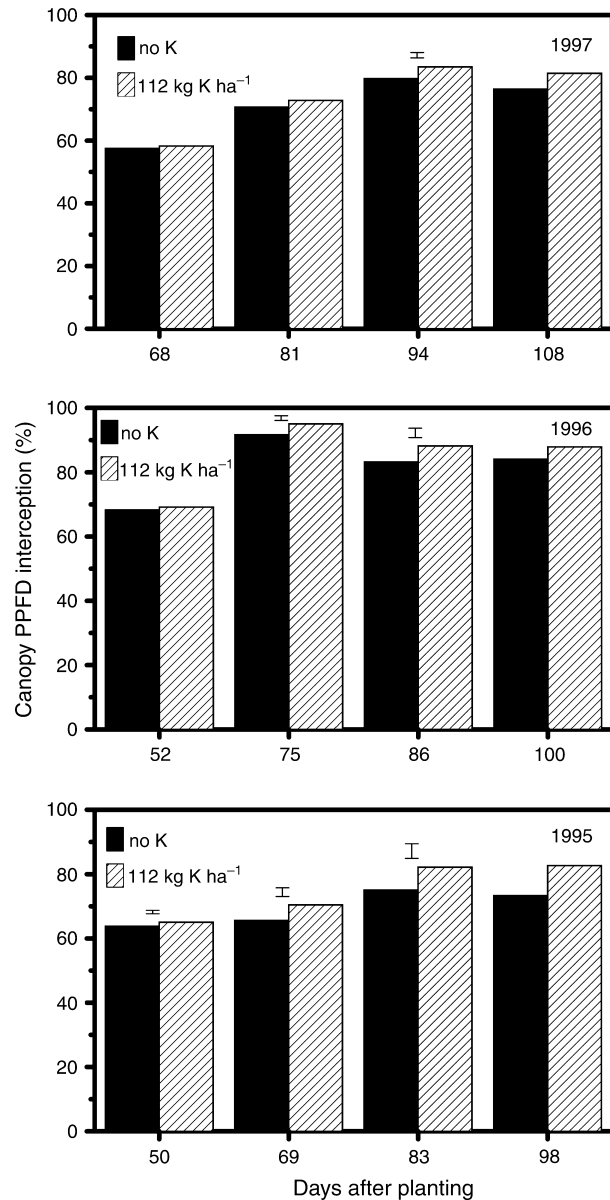


Fig. 3. Percentage PPFD intercepted by cotton canopies grown with either 0 or 112 kg K ha⁻¹ at various times throughout the 1995–1997 growing seasons. The K fertility treatment means were averaged across genotypes. Vertical bars denote LSD values at the 0.05 level and are present only when the differences between K fertility treatments are statistically significant at the 0.05 level. (Pettigrew 2003).

N rates are used (Welch and Flannery 1985). Increased ear size with K^+ fertilization also contributed to the grain yield increases seen with K^+ fertilization (Heckman and Kamprath 1992). Whereas Heckman and Kamprath (1992) reported K^+ fertilization increased the stover dry matter at maturity, Ebelhar et al. (1987) did not find that K^+ fertilization improved leaf weight or stalk weight at silking. Increased stalk weight or stover weight in

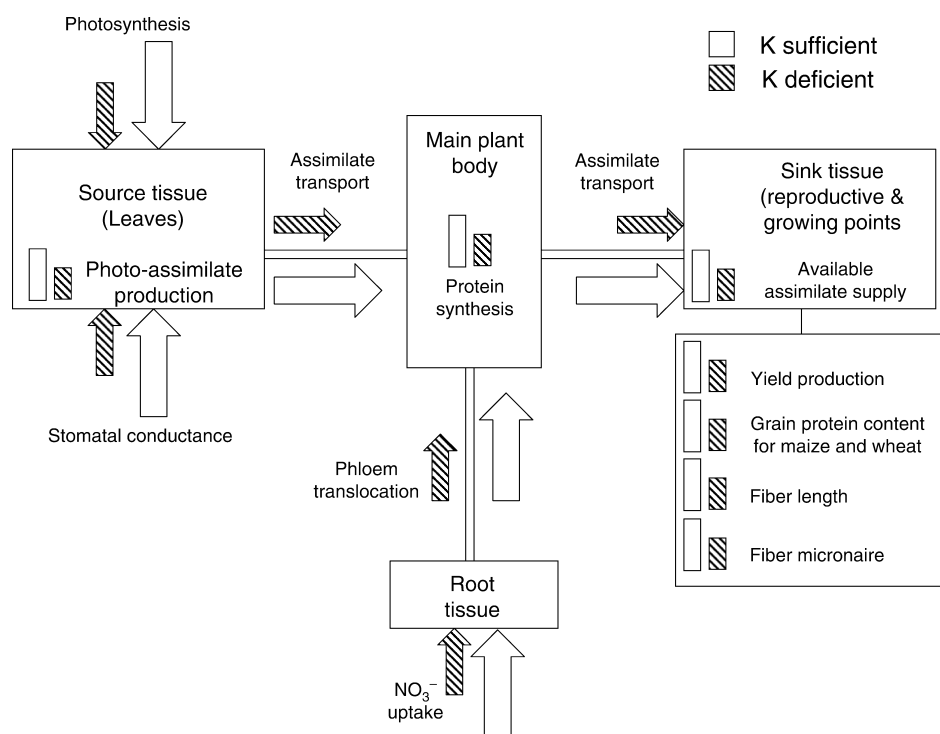


Fig. 4. Schematic diagram demonstrating the effect K has on various physiological processes and connecting those effected processes with yield and quality development (K-sufficient plants vs K-deficient plants). The production of fewer photosynthetic assimilates by the source tissue of K-deficient plants, coupled with restricted translocation of those photoassimilates out of the leaves means that a reduced assimilate pool is available to support the sink tissue (reproductive growth and other growing points) of K-deficient plants. This reduced assimilate pool contributes to the negative consequences K deficiencies have on yield and quality development.

response to K⁺ fertilization, if present, may help explain the reduced stalk lodging observed with K⁺ fertilization (Welch and Flannery 1985).

Potassium fertilization also elicits responses in soybean plants. These potassium fertilization responses can be achieved under a number of management regimes when the soil tests low for available K⁺. Soybean yield increases can be obtained with K⁺ fertilization when grown under conventional tillage (Casanova 2000, Heckman and Kamprath 1995, Jones et al. 1977), conservation tillage (Borges and Mallarino 2000, Buah et al. 2000, Coale and Grove 1990, Nelson et al. 2005, Yin and Vyn 2002, 2003, 2004), when the fertilizer was banded or broadcast (Borges and Mallarino 2000, Buah et al. 2000, Yin and Vyn 2002, 2003, 2004), and sometimes when the K⁺ is applied in a foliar application (Haq and Mallarino 2005, Nelson et al. 2005). The positive yield response to K⁺ can be attributed to increases in most of the yield components. The number of pods per plant (Bharati et al. 1986, Jones et al. 1977, Nelson et al. 1945) and the weight of individual seeds (Bharati et al. 1986) increased in response to K⁺ fertilization. Coale and Grove (1990) found that increased soybean yield under high K fertility

was because of increased production of both total and main stem pods per plant and more seeds per pod. They did not find an increase in seed size in response to K⁺ as Bharati et al. (1986) reported.

Similar to maize and soybean, yields of wheat can also benefit from potassium fertilization when native soil K⁺ levels are low (Chapman and Mason 1969, Fixen et al. 1986, Singh and Sharma 2001, Sweeney et al. 2000). There are also reports of wheat responding to K⁺ fertilization when soils tested high for exchangeable K (Fixen et al. 1986, Sweeney et al. 2000), but this phenomenon is now thought to be associated with disease suppression brought about because of the accompanying Cl⁻ ion in the frequently used murate of potash fertilizer (KCl). Similarly, Mann et al. (2004) also reported that foliar-applied KCl reduced the incidence of septoria leaf blotch in wheat. As in maize, potassium fertilization can help lessen stalk lodging in wheat (Beaton and Sekhon 1985). This yield improvement with K fertilization generally comes about because of increases in the kernel weight (Haeder and Beringer 1981, Sharma et al. 2005, Sweeney et al. 2000). Occasionally, an increase in the number of heads per unit area and the

number of kernels per head contributed to the yield increase (Haeder and Beringer 1981), but in other studies, this trend was not observed (Sweeney et al. 2000).

The previous three crops discussed were all annual crops, with the principle economic return coming from the grain that was harvested. Cotton, on the other hand, is a perennial crop that is cultured as an annual. While cotton is grown principally for its fiber or lint, there can also be economic return from the seed produced. During the late 1980s and the 1990s, late season potassium deficiency symptoms occurred in multiple cotton growing regions, prompting a great deal of cotton K fertility work. Many researchers have reported that cotton yields can be improved with K fertilization when soil K levels are insufficient (Bennett et al. 1965, Cassman et al. 1989, 1990, Clement-Bailey and Gwathmey 2007, Gwathmey and Howard 1998, Mullins et al. 1994, Pettigrew 1999, 2003, Pettigrew et al. 1996) (Table 2). The yield components responsible for the reported yield increases have been inconsistent across studies. Bennett et al. (1965) and Pettigrew (2003) found that the K fertilization induced yield increase was caused in part because of the production of a larger boll size. Multiple studies found that K fertilization lead to increased lint percentage (Cassman et al. 1990, Pettigrew 1999, Pettigrew et al. 1996). More bolls per plant were reported by Mullins et al. (1994) when K fertilization was paired with in-row subsoiling. Pettigrew (2003) also reported the production of more bolls per unit area for 1 year out of a three-year study. When soil potassium levels are insufficient, the cotton crop reaches maturity earlier (Gwathmey and Howard 1998, Pettigrew 1999, 2003). This premature cessation of reproduction growth when K⁺ levels are limiting undoubtedly contributes to the lint yield depression observed. There is also a relationship between the low K⁺ levels and the increased incidence of verticillium wilt (*Verticillium dahliae* Kleb.) infections in cotton (Hafez et al. 1975, Minton and Ebelhar 1991). On soils with histories of verticillium wilt problems, some of the yield improvements produced from K fertilization may be related to suppression of this disease.

While this yield improvement response to K fertilization on low K testing soils is a fairly uniform response, there can be genotypic variation for this response. This phenomenon has been demonstrated in cotton. While Pettigrew et al. (1996) did not find any genotypic differences in the lint yield response to potassium fertilization among the group of eight genotypes used, Halevy (1976), Cassman et al. (1989), Pettigrew et al. (2005) and Zhang et al. (2007) all identified genotypes that were more responsive to K⁺ fertilization than other genotypes. Furthermore, the more potassium responsive genotype in the study by Cassman et al. (1989) was subsequently shown to produce a more extensive root system than the less K⁺ efficient genotype (Brouder and Cassman 1990). Therefore, the genotypic differences in K⁺ response are probably because of the fact that more K⁺ responsive genotypes were able to take up K⁺ at a greater rate or more efficiently because of a bigger root system. Clement-Bailey and Gwathmey (2007) also reported that K⁺ fertilization was more critical for early-maturing cotton varieties rather than later maturing varieties, but Pettigrew (2003) did not find maturity to play a role in the responsiveness of leaf-type isolines to K⁺ fertilization.

Genotypic differences for K⁺ uptake and use efficiencies have also been detected in other crops. Maize hybrids were demonstrated to differ in K⁺ uptake efficiencies (Allan et al. 1998), with the more efficient K⁺ uptake hybrid was also being the highest yielding. Varga et al. (2004) reported that prolific maize hybrids responded more favorably than non-prolific hybrids to high-input cropping systems (including additional K⁺ fertilization), primarily by increasing kernel weights and yield. Although a K⁺ deficiency tolerant maize hybrid produced more dry matter and an increased number of lateral roots than a K⁺ deficiency sensitive hybrid, the sensitive hybrid actually possessed longer taproots (Minjian et al. 2006). Genotypic differences among wheat varieties have also been detected in K⁺-use efficiency (gram of dry matter per gram K⁺) for both grain and stalk production (Bassam 1998). Damon and Rengel

Table 2. Cotton lint yield and yield components as affected by K fertility levels and N fertility levels averaged across eight genotypes and the years 1991 and 1992 (Pettigrew et al. 1996). ^ans, not significantly different at $P \geq 0.05$.

N application rate	K application rate	Lint yield (kg ha ⁻¹)	Boll mass (g boll ⁻¹)	Lint percentage (%)	Seed mass (mg seed ⁻¹)
112 kg N ha ⁻¹		1256	4.24	39.0	92
150 kg N ha ⁻¹		1241	4.25	38.9	92
LSD (0.05)		ns ^a	ns	ns	ns
	0 kg K ha ⁻¹	1188	4.13	38.6	90
	112 kg K ha ⁻¹	1309	4.36	39.3	94
	LSD (0.05)	31	0.13	0.3	2

(2007) detected wheat genotypic differences in the K^+ efficiency ratio (the ratio of growth at deficient and adequate K supply). Furthermore, a wheat mutant was identified that accumulated more K^+ in the leaf tissue than the wild-type line (Rascio et al. 2001). In addition, soybean varieties have also been demonstrated to differ in total K^+ uptake with these total K^+ uptake differences associated with yield potential (Hanway and Weber 1971).

There can be many physiological aspects where genetics can intercede and lead to the overall variability among genotypes in the response to K^+ fertilization. Most of these aspects have been detailed in the review article for this series by Rengel and Damon (2008). Without going into too much detail, these physiological aspects include: (1) root morphology; (2) root hairs; (3) root exudates; (4) K^+ release from unexchangeable pools; (5) kinetics of K^+ uptake; (6) translocation; (7) substitution and (8) harvest index. The first five physiological traits listed are involved with K^+ uptake efficiency, while the later three traits are involved in K^+ utilization efficiency. Most of these traits mentioned by Rengel and Damon (2008) represent areas geneticists and breeders might target to produce more nutrient-use efficient breeding lines.

Crop quality

The revenue an agricultural producer receives from the marketplace is derived from two functions: (1) the amount of product delivered to the market and (2) the quality of the product delivered to the market. Although product quantity is the principal function driving the producer's revenue stream, product quality can also determine some of this economic return. In fact, for some crops, quality plays an increasing role and in some cases the dominant role in generating revenue. Potassium can play a role in quality development of many crops (Usherwood 1985). When supplemental K^+ fertilization was applied to maize, it produced an increase in the grain protein content and amino acid content (Usherwood 1985). Supporting this high grain protein concept are the findings of Yang et al. (2004) that when maize was grown without manure in China, a greater grain protein content was produced using a balanced N-P-K fertilizer rather than using a fertilizer composed of only N and P. Similar to the response observed with maize, K^+ fertilization is often found to elicit an increase in wheat grain protein and amino acid contents (Koch and Mengel 1977, Mengel et al. 1981). In contrast, Boquet and Johnson (1987) reported that K^+ fertilization did not alter the grain protein content in soft red winter wheat. This increased grain protein in response to K^+ fertilization, when pre-

sent, can be explained by favorable effect K^+ has on protein production (Blevins 1985), NO_3^- uptake and transport within the plant (Blevins et al. 1978a) and amino acid transport (Mengel et al. 1981).

Soybean is a crop where both the seed oil content and the seed protein contribute to the economic value, and there is generally an inverse relationship observed between the seed protein and the oil content (Weber 1985). This inverse relationship was demonstrated by Gaydou and Arrivets (1983) and Yin and Vyn (2003) as they found potassium fertilization to increase seed oil content while decreasing seed protein content. Gaydou and Arrivets (1983) also found that seed linoleic acid content was increased by K^+ fertilization, while the oleic acid content was decreased. In contrast, Haq and Mallarino (2005) and Seguin and Zheng (2006) did not find consistent results from K^+ fertilization on seed oil and protein content. Soybean seeds also contain isoflavones, a group of phytochemicals thought to provide human health benefits. Vyn et al. (2002) and Yin and Vyn (2004) reported that K^+ fertilization increased the isoflavone concentration of the seeds. However, Seguin and Zheng (2006) did not find K^+ fertilization to affect isoflavone content, but the soils used in their study exhibited a medium to high initial fertility level.

With cotton, the most important quality considerations pertain to the lint, although there can be some economic value to having better quality seed. The fiber quality parameters that help determine the marketing loan value from the US Department of Agriculture – Agriculture Marketing Service are fiber length, length uniformity, fiber strength, micronaire, the color grade and the leaf grade. Potassium has been implicated in the determination of many of these fiber traits; however, the effect on individual traits has been inconsistent across studies. Micronaire, an estimate of the fiber fineness, is generally decreased when insufficient K^+ levels are present during growth (Bennett et al. 1965, Cassman et al. 1990, Pettigrew 1999, 2003, Pettigrew et al. 1996) (Table 3). However, Minton and Ebelhar (1991) did not find micronaire to respond to K^+ fertilization. Both components of micronaire, fiber maturity and fiber perimeter can be reduced when K^+ levels are insufficient (Pettigrew 1999, Pettigrew et al. 1996). Micronaire and fiber maturity are closely associated with the degree of cellulose deposition into the fiber secondary cell wall. Any disruption in the supply of photosynthetic assimilates to the fiber will decrease the amount of cellulose deposited into the secondary cell wall and thereby reduce fiber maturity and micronaire. Therefore, the previously mentioned K^+ deficiency induced reduction in photosynthetic assimilates, both from lower photosynthetic rates (Bednarz et al. 1998, Longstreth and Nobel 1980,

Table 3. Fiber quality characteristics as affected by K levels averaged across 1991 and 1992. (Pettigrew et al. 1996). ^ans, not significantly different at $P \geq 0.05$.

K application rate	Fiber strength (kN m kg ⁻¹)	Fiber elongation (%)	Span length (cm)		Uniformity ratio	Micronaire	Fiber maturity (%)	Fiber perimeter (μm)
			2.5%	50%				
0 kg ha ⁻¹	207	7.97	2.82	1.35	48.0	3.7	74.1	49.1
112 kg ha ⁻¹	203	8.25	2.82	1.37	48.7	4.1	78.3	49.2
LDS (0.05)	ns ^a	0.25	ns	0.01	0.4	0.1	1.6	0.1

Pervez et al. 2004) and less leaf area (Pettigrew 2003, Pettigrew and Meredith 1997) coupled with reduced transport from the photosynthetic sources to reproductive sinks (Ashley and Goodson 1972) contribute to these lower fiber maturities and micronaire seen with lower K⁺ levels.

Most previous cotton potassium studies have documented the production of shorter fibers when the plants were grown under insufficient K⁺ conditions (Bennett et al. 1965, Cassman et al. 1990, Pettigrew 1999, 2003, Pettigrew et al. 1996). This outcome is not surprising considering that Dhindsa et al. (1975) previously demonstrated how K⁺ and malate served as the osmotica to produce the turgor pressure that drives cotton fiber cell elongation. Thus, when K⁺ supplies are insufficient, the fiber osmotic potential would be higher (less negative) and unable to produce the turgor pressure needed for elongation of the primary fiber cell wall, resulting in shorter fibers.

The responses of both fiber strength and fiber elongation (the increased fiber length at the breaking load during a strength test expressed as a percentage of the original length) to different levels of K⁺ fertilization have been inconsistent. Whereas Cassman et al. (1990) and Minton and Ebelhar (1991) reported weaker fibers when grown with insufficient K⁺ levels, Bennett et al. (1965), Pettigrew et al. (1996) and Pettigrew (2003) did not detect any fiber strength differences among different K⁺ fertility treatments. Cassman et al. (1990), Pettigrew et al. (1996) and Pettigrew (1999, 2003) all found that deficient K⁺ levels lead to reduced fiber elongation, but Bennett et al. (1965) and Minton and Ebelhar (1991) did not detect this fiber elongation response. These inconsistencies in the response of fiber strength and fiber elongation to varying K⁺ treatments indicate that K⁺ probably only exerts an indirect effect on these two fiber traits.

This article reviewed the ways in which K⁺ impacts the underlying physiological processes that determine crop yield and quality production and then traces how these impacted physiological processes alter the resulting yield and quality. With the ever increasing costs of the inputs involved in producing a crop, future research might well

be directed toward determining ways that the plant can make more efficient use of the potassium available to it. As suggested by Cassman (1998), an improvement in K-use efficiency would probably be best accomplished by first developing crop genotypes with larger or improved root systems to more efficiently remove K from the soil (either native K or fertilizer applied). Of course, for this improvement in K uptake efficiency to effectively translate into more efficient use of the K or improved yields, other potential rate limiting steps or bottlenecks must also be removed or mitigated.

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